

National Aeronautics and
Space Administration



ARSET

Applied Remote Sensing Training

<http://arset.gsfc.nasa.gov>

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MERRA-2 Reanalysis

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(Based on Slides from Arlindo da Silva and GMAO Team)

Satellite Remote Sensing of Air Quality

September 19-21, 2017

University of California, Riverside

Learning Objectives

By the end of this presentation, you will be able to:

- Learn about NASA MERRA Reanalysis data sets
- Learn to access data and tools for AQ applications

Why data assimilation?

- Models are useful, but have difficulty specifying emissions, microphysical processes, and transport leads to large uncertainties
- While there are a large number of aerosol sensors, there are still blind spots:
 - Measurements are usually vertically integrated
 - Diurnal cycle is not represented by polar orbiters
- Data assimilation can act as an integrator of model and observational information and a conveyor of past observations

What is reanalysis, and why do we do it?

What

- Relies on models to interpret, relate, and combine different observations from multiple sources
- A consistent reprocessing of Earth system observations using a modern, unchanging data assimilation system
- A successful reanalysis **requires** a good forecast model combined with bias-corrected and quality controlled observations

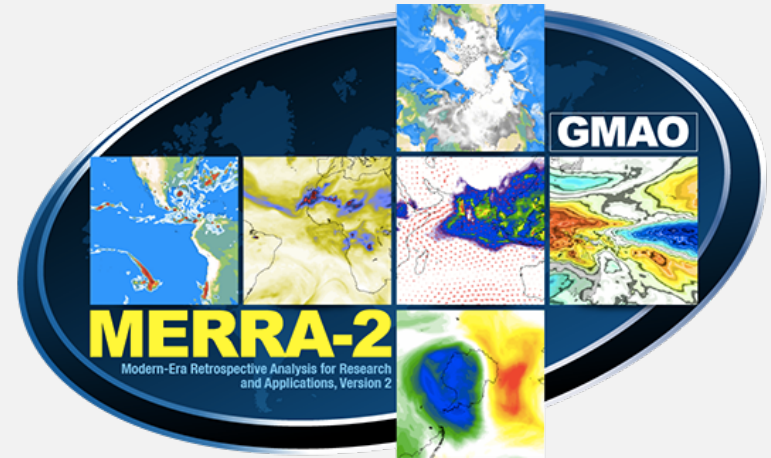
Why

- Produces multi-decadal, gridded datasets that estimate a large variety of Earth system variables, including ones that are not directly observed
- Has become fundamental to research and education in the Earth sciences

MERRA Reanalysis

<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>

- Long-term, model-based analyses of multiple datasets using a fixed assimilation system
 - GEOS (Goddard Earth Observing System Model)
- The **Modern-Era Retrospective analysis for Research and Applications** (MERRA) provides data beginning in 1980 and runs a few weeks behind real-time
- MERRA-2 includes meteorology, stratospheric ozone, and aerosols at a spatial resolution of a $0.5^\circ \times 0.66^\circ$ grid



Source: <https://gmao.gsfc.nasa.gov/reanalysis/>

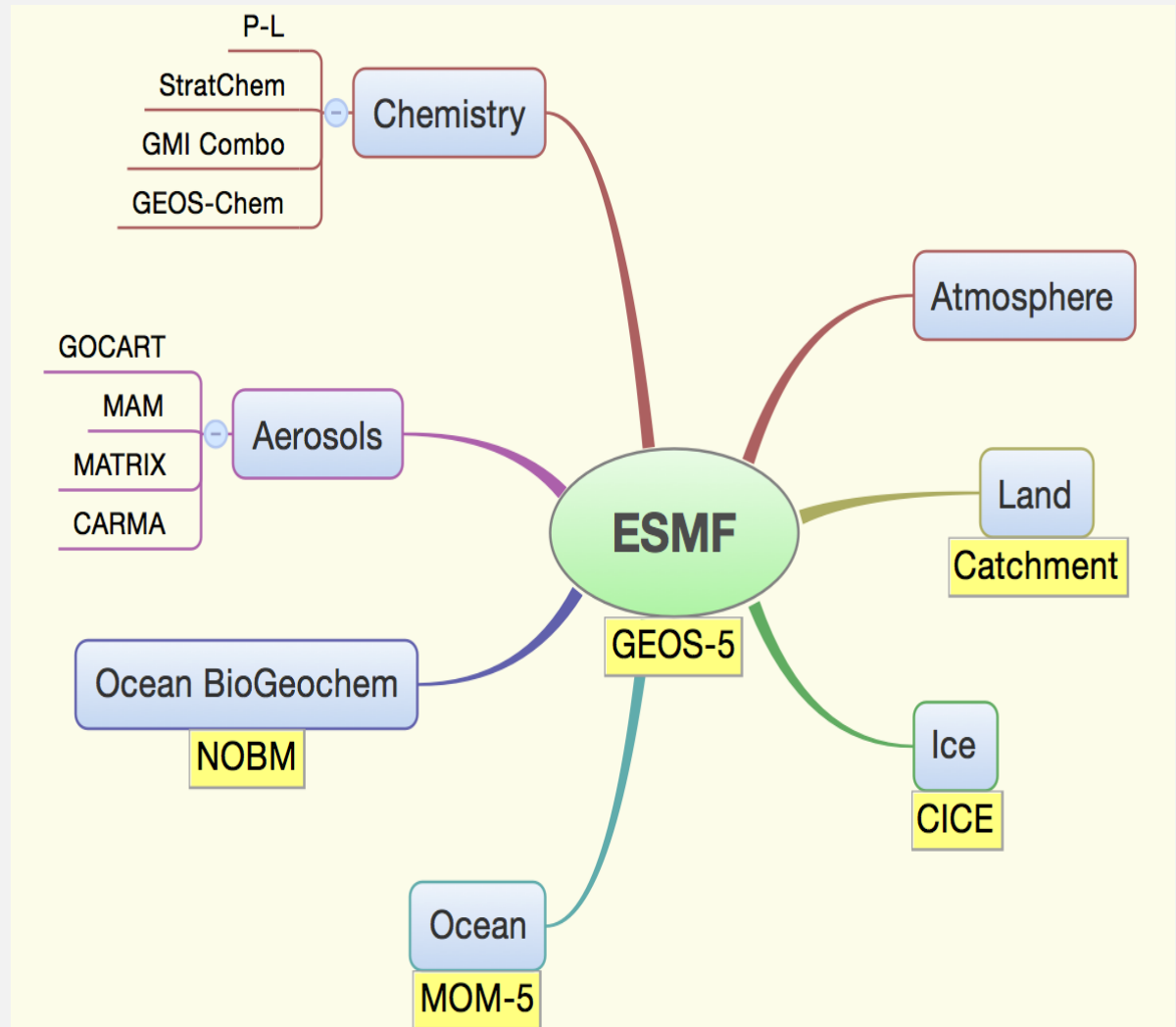
GEOS-5 Reanalysis Activities

Name	Nominal Resolution	Period	Aerosol Data	Available
MERRA-1	50 km	1979 – present	NONE	now
MERRAero	50 km	2002 – present	MODIS C5	now
Forward Processing for Inst. Teams	50 km	1997 - present	MODIS C5	In progress
NCA	25 km	2010 – 2011	MODIS C5, MISR	Now
MERRA-2	50 km	1979 – present	AVHRR, MODIS C5, MISR, AERONET	Summer 2015
MERRA-2 Dynamical Downscaling	12.5 km	2000 – 2014	AVHRR, MODIS C5, MISR, AERONET	Q4 2015

GEOS-5

Earth System Model

- Components coupling via the Earth System Model Framework (ESMF)
- Aerosol and chemistry radiatively coupled to GCM
- Applications
 - Seasonal forecasts
 - Weather and aerosol NRT forecasts
 - Reanalysis
 - Observing System Simulation Experiments (OSSEs)



Radiance Assimilation into MERRA

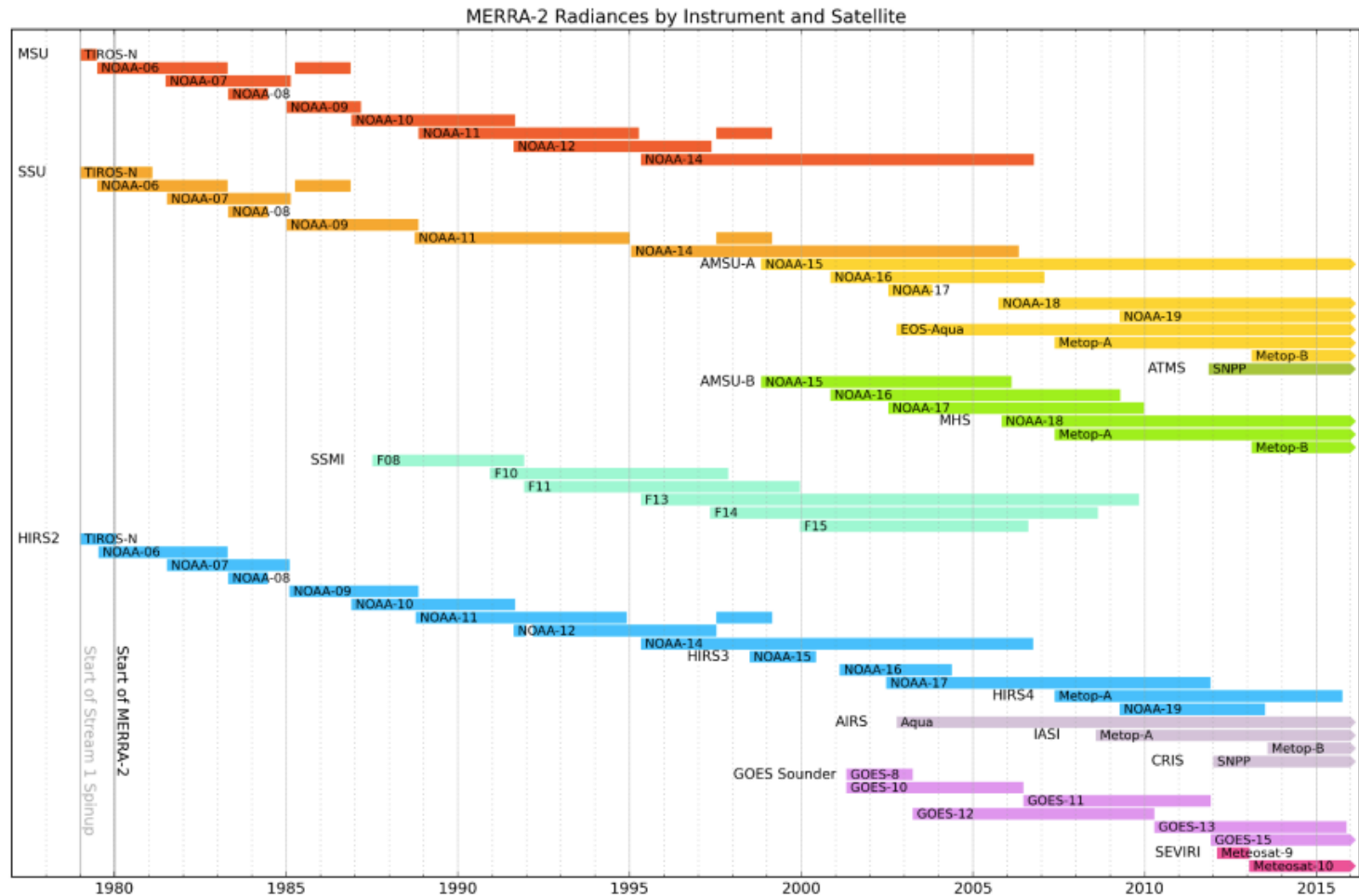
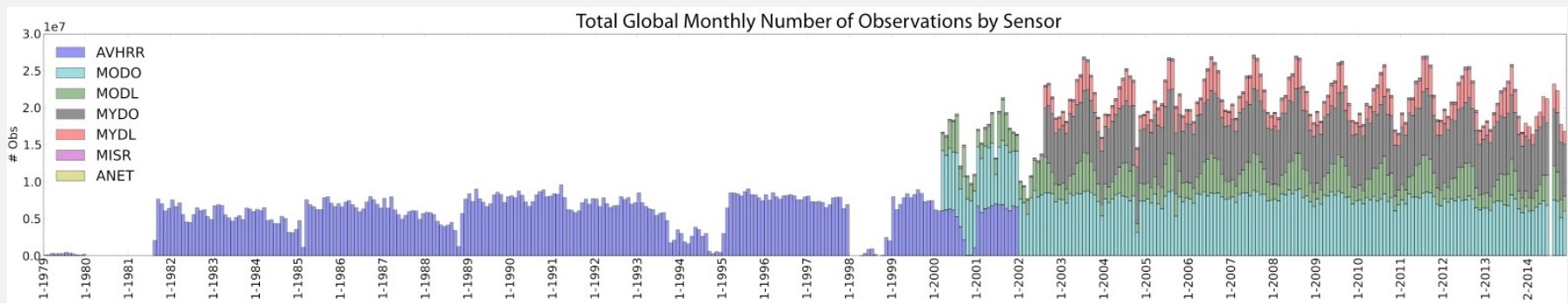


Figure 5 - Timeline of satellite radiance observations over the entire MERRA-2 period. Each bar is colored by instrument type and represents a satellite from which the instrument measured.

Aerosol Observing System

Sensor	Period	Remarks
AVHRR*	1979 – 2002	PATMOS-x; NNR; Ocean Only
AERONET	1999 – 2015	Ground-Based Stations
MODIS Terra*	2000 - present	C5; NNR; Separate Land and Ocean
MODIS Aqua*	2002 – present	C5; NNR; Separate Land and Ocean
MISR	2000 – 2014	Bright Surfaces (albedo > 0.15)

Total global monthly number of AOD observations (below), sensors marked with * multiplied by 10^7)



GOCART in GEOS-5

- Based on the Goddard Chemistry, Aerosol, Radiation and Transport Model (Chin et al. 2002)
- Sources and sinks for 5 non-interactive species



- Convective and large scale wet removal
- Dry deposition (and sedimentation for dust and sea salt)
- Optics based primarily on OPAC

MERRA-2 Emissions

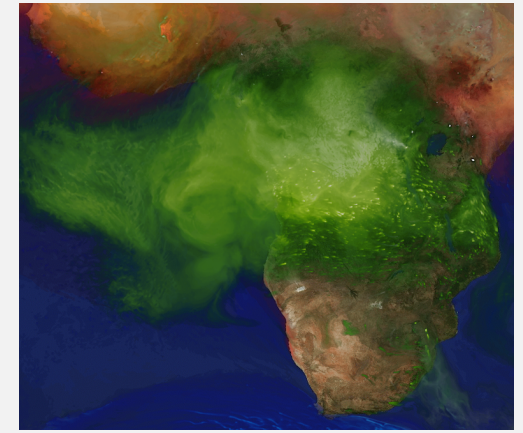


Table 1: Aerosol emissions databases (native temporal and spatial resolutions).

Aerosol Type	Source	Temporal Resolution	Spatial Resolution ^{a,b}
Dust ^c	Wind-driven emissions w/? source	Annual-mean climatology	$0.3125^\circ \times 0.25^\circ$
Sea Salt	Wind-driven emissions	Model	Model
Volcanic (SO ₂)	AeroCom Phase II (HCA0 v2)	Daily	Point-sources
Biogenic terpene	GEIA	Monthly-mean climatology	$2^\circ \times 2.5^\circ$
DMS	Lana <i>et al.</i> 2011	Monthly-mean climatology	$1^\circ \times 1^\circ$
Biomass Burning (SO ₂ , OC and BC) ^d	HFED	Monthly-varying	0.5
Biomass Burning (SO ₂ , OC and BC) ^e	QFED-2.4r6	Daily	$0.3125^\circ \times 0.25^\circ$
Anthropogenic SO ₂ and SO ₄	EDGARv4.2 (Energy + Non-Energy)	Annually-varying	$1^\circ \times 1^\circ$
Anthropogenic OC and BC	AeroCom Phase II (HCA0 v1)	Annually-varying	$1^\circ \times 1^\circ$
Ship (SO ₂ , SO ₄ , OC, BC)	EDGARv4.1 and ?	Annually-varying	$1^\circ \times 1^\circ$
Aircraft (SO ₂)	AeroCom Phase II (HCA0 v1)	Monthly-varying	$1^\circ \times 1.25^\circ \times 72\text{-levels}$

^a Model = MERRA-2 time-step of 30 minutes with spatial resolution of 0.5° latitude \times 0.625° longitude.

^b latitude \times longitude

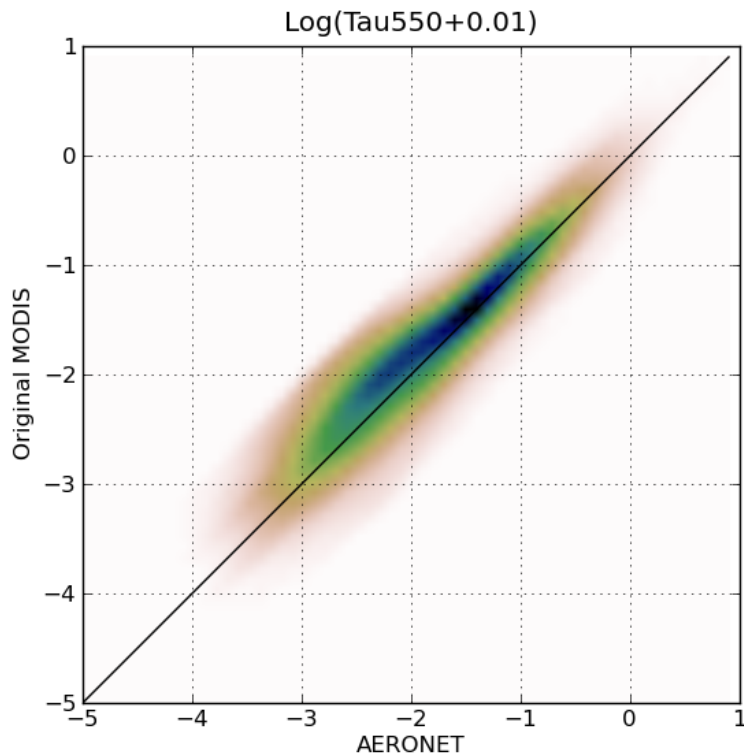
^c Resolution is for source map (Ginoux *et al.* 2001); wind-driven emissions at model time-step.

^d Streams 1-3; Y1979-Y2010

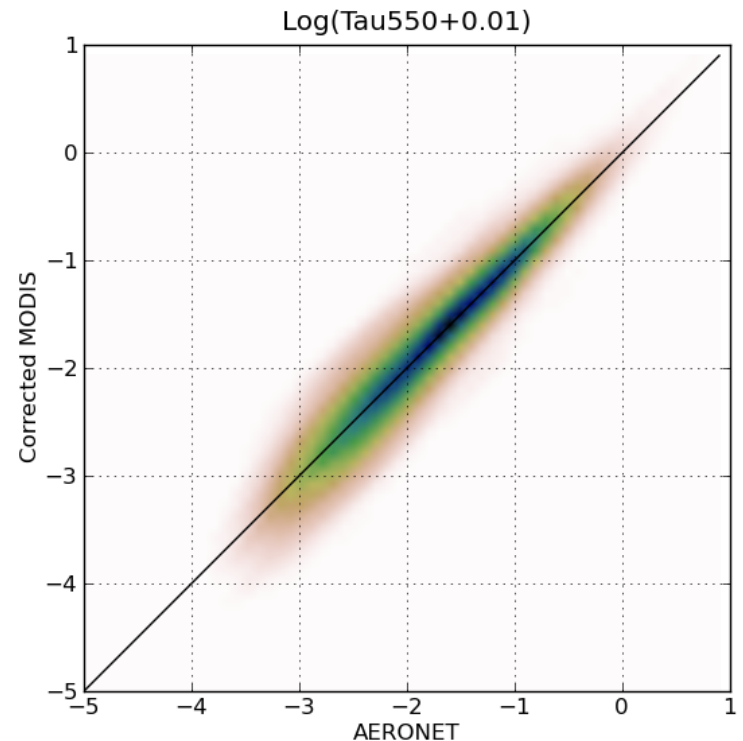
^e Stream 4; Y2010-onward

Observational Bias in AODs

Original MODIS AOD



Bias Corrected AOD

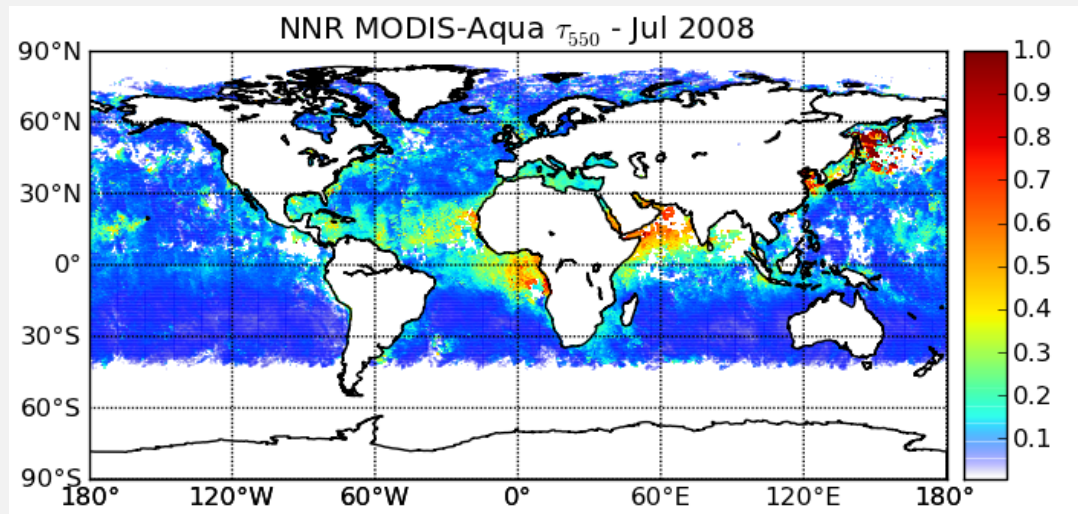
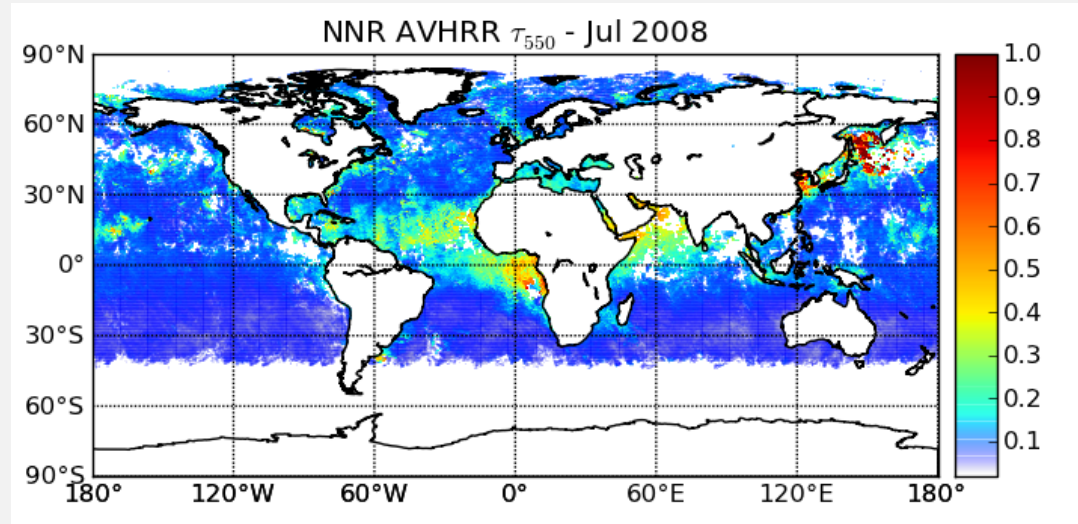



MODIS Neural Net AOD Retrievals trained on AERONET

Observing System Homogenization

In order to minimize spurious jumps due to relative instrument biases, MERRA-2 uses AERONET as a reference in a series of Neural Net Retrievals (NNR) based on reflectances from:

- MODIS Collection 5
- PATMOS-X AVHRR

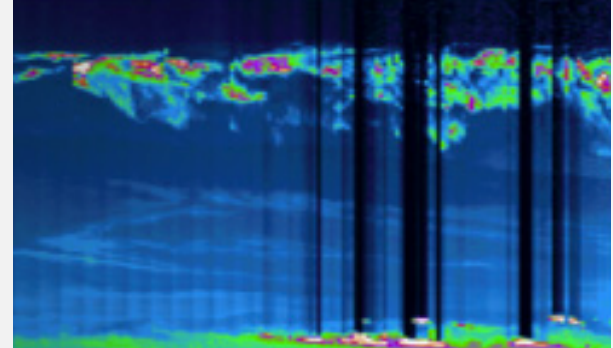


A satellite image of the Mediterranean Sea and surrounding landmasses, including North Africa, the Middle East, and parts of Europe. A semi-transparent rectangular box is overlaid on the sea, containing the text 'Evaluation & Intercomparisons'. Red outlines on the land indicate specific regions of interest.

Evaluation & Intercomparisons

MERRA-2 Aerosol Evaluation Highlights

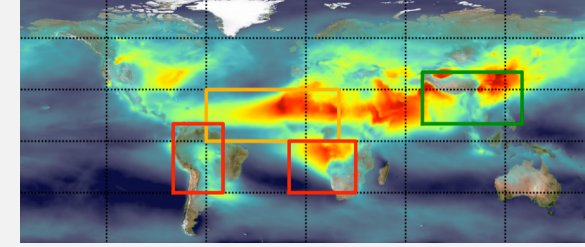
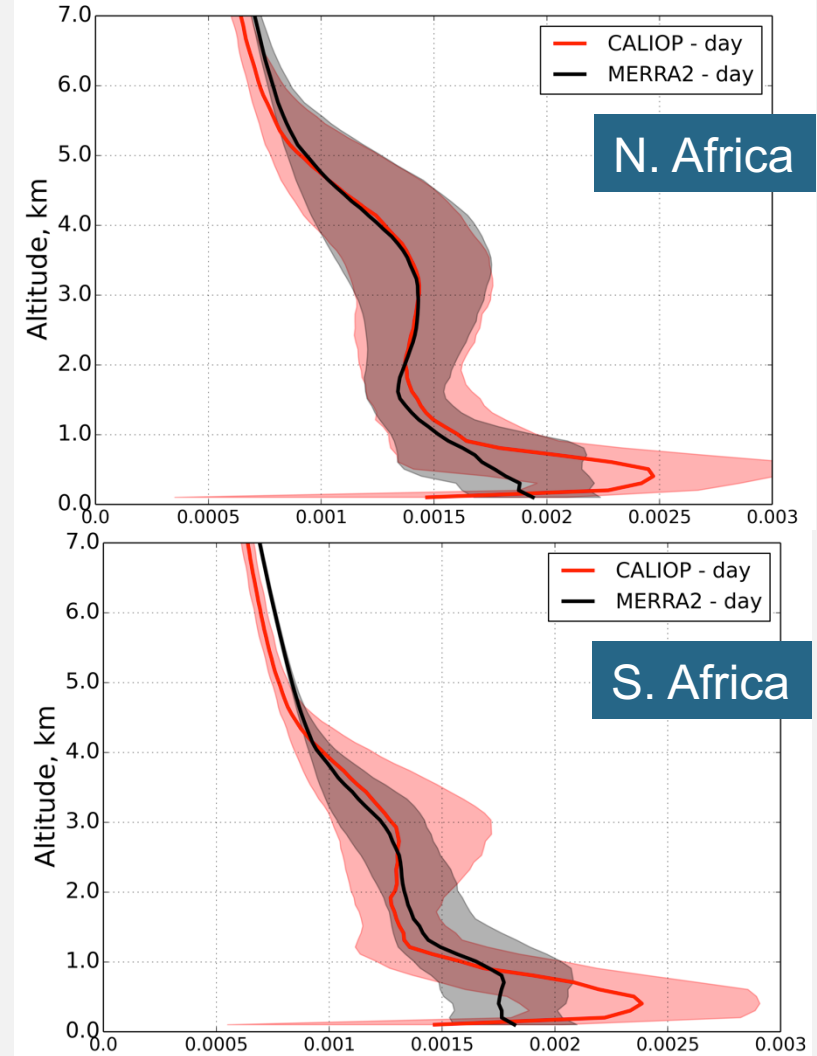
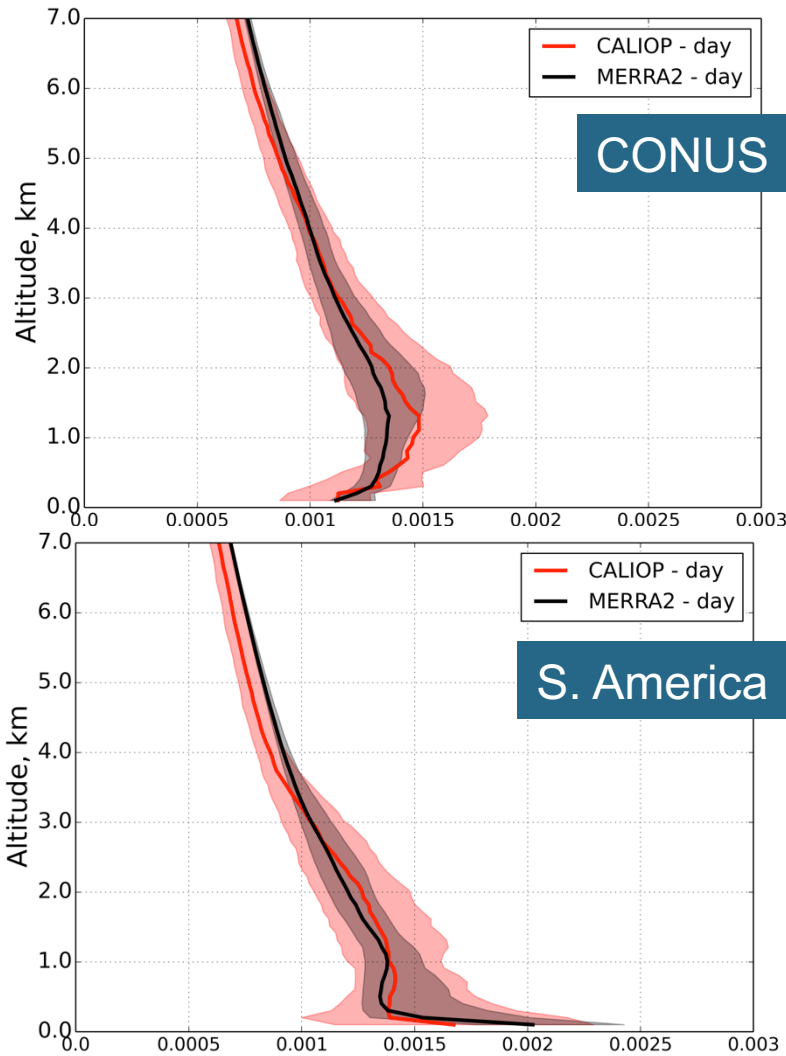
Using Independent Observations



Vertical Structure

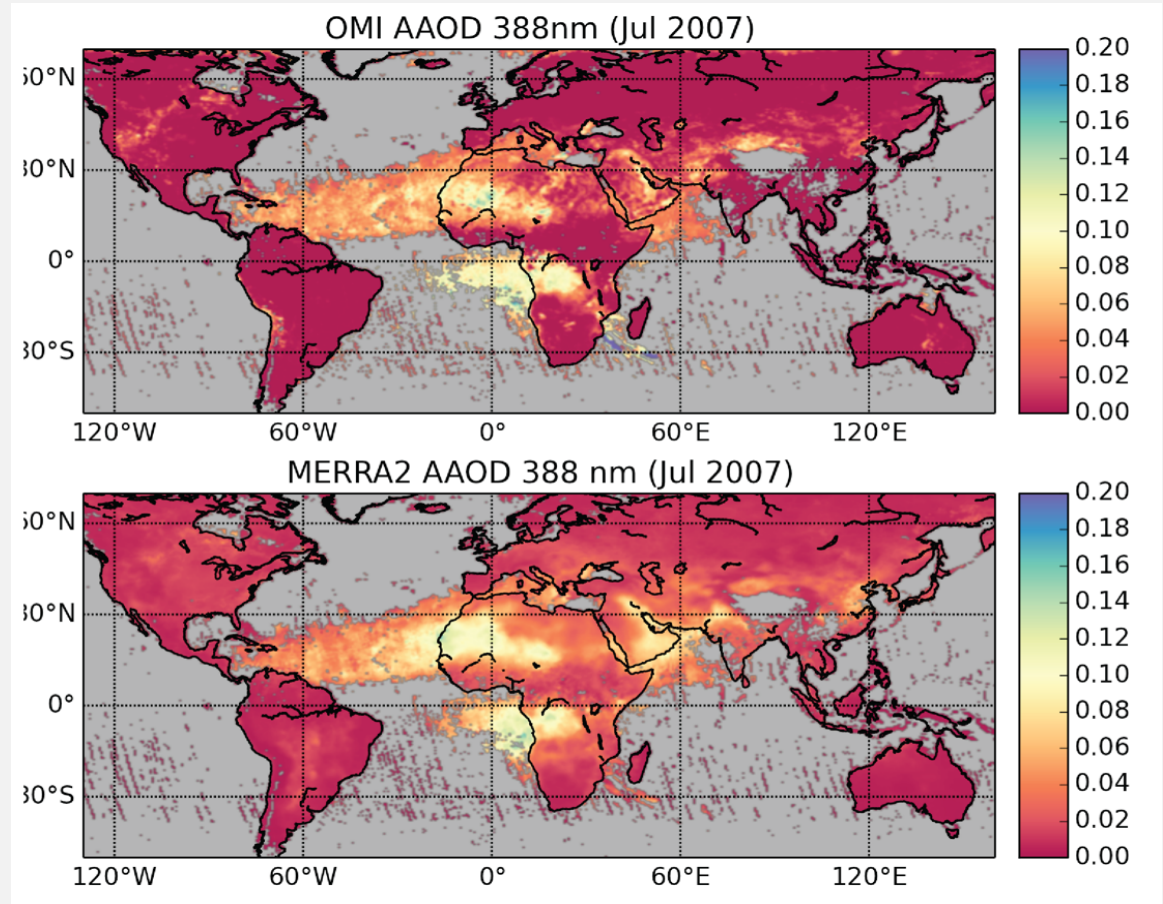
Comparison to CALIOP

Attenuated Backscatter $\text{km}^{-1} \text{sr}^{-1}$

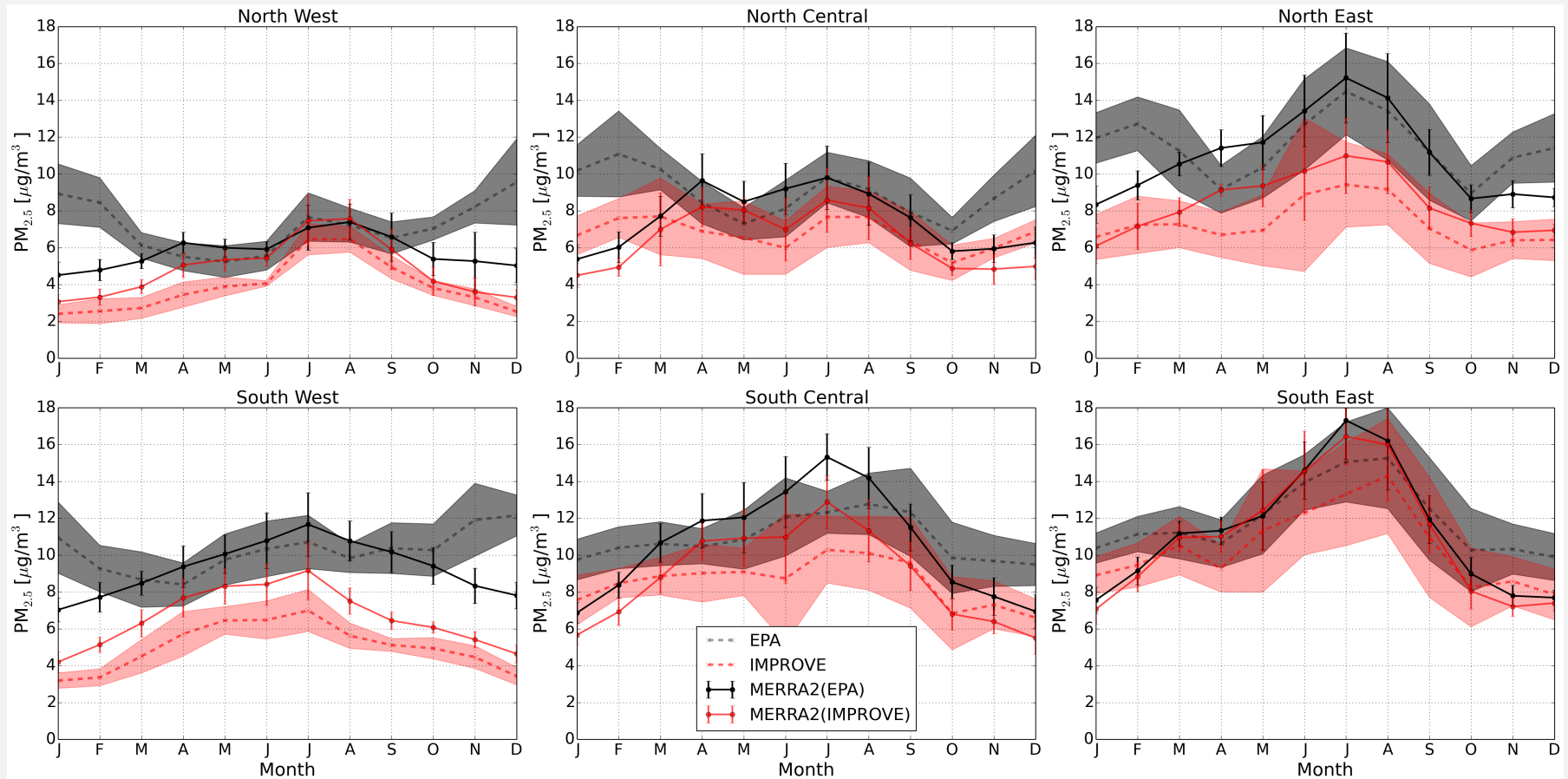
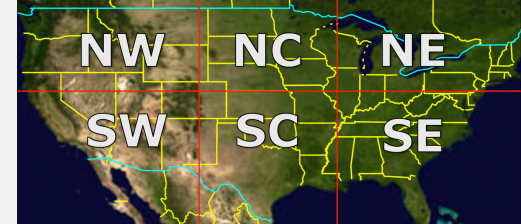


Aerosol Absorption

- Comparison of MERRA-2 Absorption Optical Depth (AAOD) with OMI retrievals
- Good agreement for African dust and smoke
- North American biomass burning underestimated according to OMI



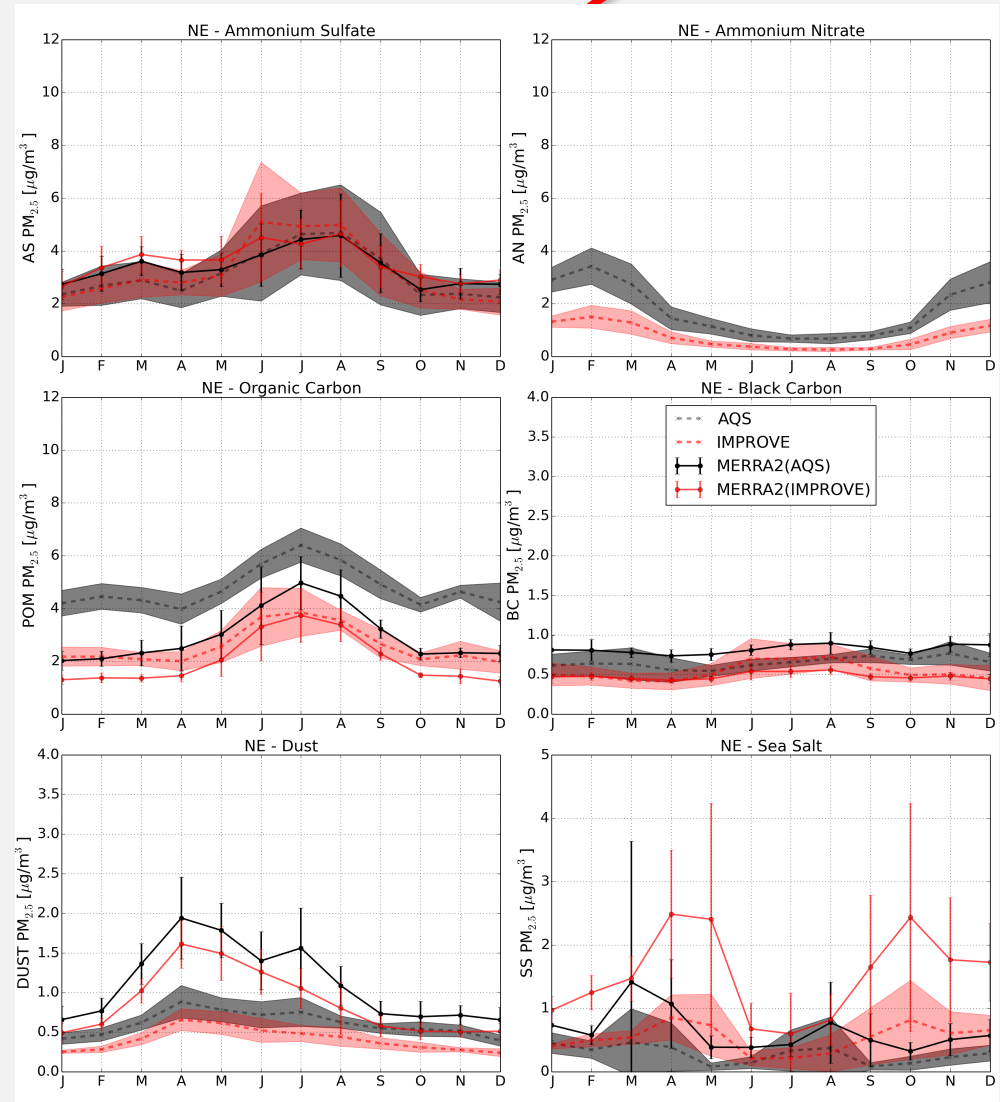
PM_{2.5} (Total) Regional Climatology



Comparison with in-situ measurements after *Buddy Check*

PM_{2.5} by Species in the Northeast

- Relatively good agreement for **sulfates**
- MERRA-2 lacks **nitrates** altogether
- Underestimation of **carbonaceous** near-urban areas
- Too much **dust**
- Too much **sea salt** at coastal stations



A satellite image of the Mediterranean Sea and surrounding landmasses, including North Africa, the Middle East, and parts of Europe. A semi-transparent rectangular box is overlaid on the sea, containing the text 'Data Access & Tools'. Within this box, there are several red outlines and dots on the landmasses, likely indicating specific regions of interest or data collection points. The text 'Data Access & Tools' is positioned in the lower-left corner of the box.

Data Access & Tools

MERRA-2 Webpage Tour

<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>



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MERRA-2 Project

Data Access

Documentation

Highlights

Images

Videos

FAQ

Publications

Mailing List

User Metrics

Diagnostic Feedback

Modern-Era Retrospective analysis for Research and Applications, Version 2

Project Overview

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) provides data beginning in 1980. It was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enable assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets. It also uses NASA ozone observations after 2005. Additional advances in both the GEOS-5 model and the GSI assimilation system are included in MERRA-2. Spatial resolution remains about the same (about 50 km in the latitudinal direction) as in MERRA.

Along with the enhancements in the meteorological assimilation, MERRA-2 takes some significant steps towards GMAO's target of an Earth System reanalysis. MERRA-2 is the first long-term global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system. MERRA-2 includes a representation of ice sheets over (say) Greenland and Antarctica.



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MERRA-2 Status

- MERRA-2 has officially been released. Data access through the GES DISC:
 - <http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset2.pl>
 - <http://disc.sci.gsfc.nasa.gov/uui/#/search/%22MERRA-2%22>
- The MERRA-2 file specification document is available at:
 - <http://gmao.gsfc.nasa.gov/pubs/> under the tab *Office Notes*
- NASA tech memos documenting the MERRA-2 meteorological and aerosol validation exercise will soon be available at:
 - <http://gmao.gsfc.nasa.gov/pubs/> under the tab *Technical Memoranda*

MERRA Tools

 EARTHDATA

Find a DAAC ▾







GES DISC

Atmospheric Composition, Water & Energy Cycles and Climate Variability

Tools ▾





Enter search (e.g., rainfall, GPM, TRMM_3B42)




 Feedback


Help ▾

Login



 **Tools** Showing 1 - 8 of 8 tools

Sort by : Last Updated ▾



Hydrology Data Rods


Brief description of what data rods are, what problems they address, and what data sets and user communities they serve.

AIRS NRT Viewer

A web-compatible map viewer for selected AIRS near real-time (NRT) data


OGC Web Map Server (WMS)

GES DISC OGC Web Map Server (WMS) instances which allow users to access various GES DISC science data products in the form of geo-registered maps/images.



MERRA Subsetter

A subsetter targeted specifically towards MERRA data; supports spatial, variable, time-of-day, and vertical level subsetting.



Data Quality Visualization

A web-compatible tool providing services to visualize and analyze multiple satellite sensor level-2 products with MERRA-2 model simulations, specializing in quality-assurance data parallel comparison

OPeNDAP and GDS

This page serves as a catalog and quick entry point to OPeNDAP (and alike) Web Services at GES DISC, such as OPeNDAP (Hyrax), TDS (THREDDS), GDS (DODS), and Pomegranate.

OpenDAP server

Model Data

Project or Mission	Description	Web Services
LDAS	GLDAS-2, NCA-LDAS, FLDAS, and GRACE-DA-DM	OPeNDAP
	GLDAS and NLDAS	GDS
MERRA	MERRA Chemistry forcing	OPeNDAP GDS
	MERRA 2D products	OPeNDAP GDS
	MERRA 3D products	OPeNDAP GDS
MERRA-2	MERRA-2 2D products	OPeNDAP GDS
	MERRA-2 3D products	OPeNDAP GDS
NOBM	NOBM daily and monthly	OPeNDAP

Science Focus Areas

Atmospheric Composition
Water & Energy Cycles
Climate Variability

Tools

Giovanni
MERRA Subsetter
Data Rods for Hydrology
DQViz
AIRS NRT Viewer
OGC Web Map Service
OPeNDAP and GDS

Resources


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Citing Our Data
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MERRA-2 Data Access – GES DISC - Subsetter


 **EARTH DATA**

Data Discovery ▾ DAACs ▾ Community ▾ Science Disciplines ▾



GES DISC

Atmospheric Composition, Water & Energy Cycles and Climate Variability



Data Product

First Select Data Product:


Spatial Search

Bounding Box: (minLon, minLat, maxLon, maxLat)

+

-


□



Leaflet

Temporal Order Option

You may order data from a range of days using the selection boxes below. Please refer to the calendar to identify days with available data. An excessive range of days may cause processing delays or exceed the amount of data that may be ordered.

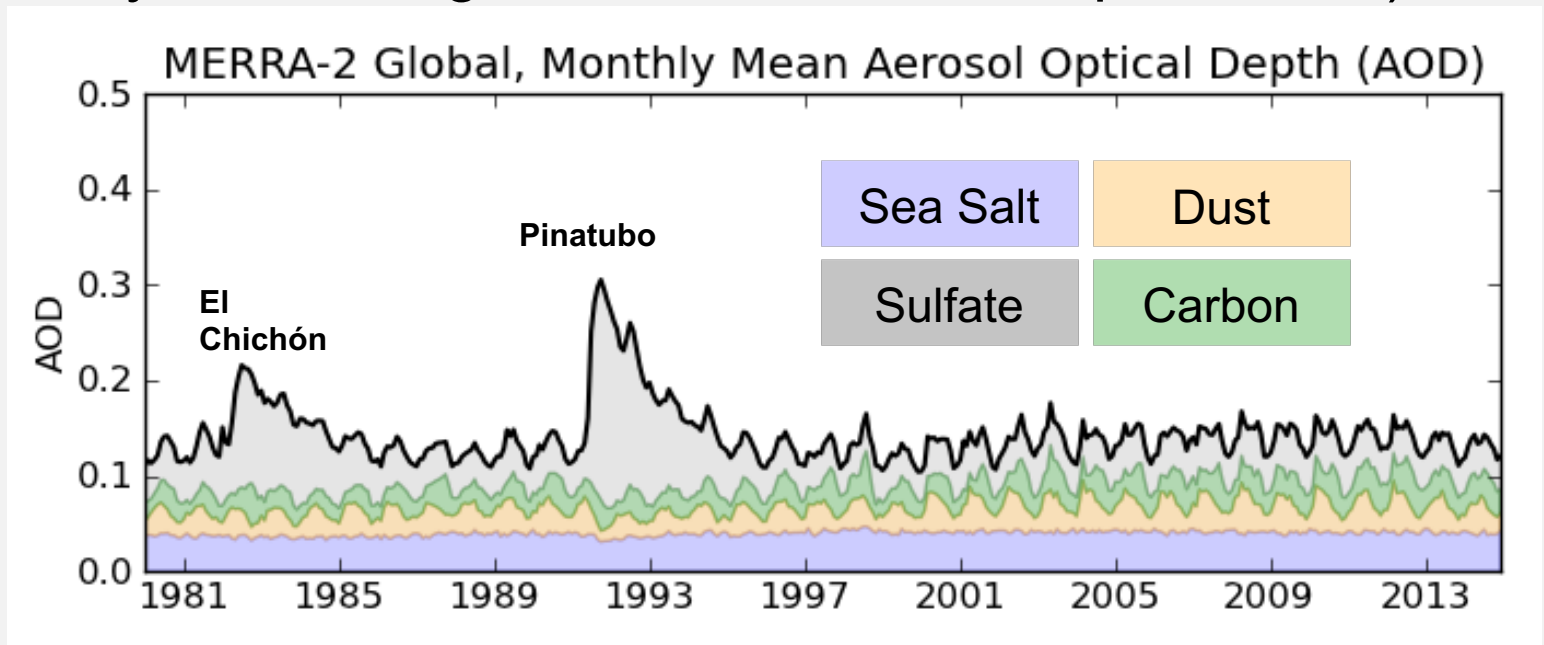
A satellite image of the Mediterranean Sea and surrounding landmasses. A semi-transparent gray rectangular box is overlaid on the sea, containing the text 'Examples – Applications'. The box is positioned in the lower-left quadrant of the image. The sea is a deep blue, and the surrounding land is a mix of brown, tan, and green, indicating various terrain types. There are some red markings on the land, possibly indicating specific locations or features. The text 'Examples – Applications' is in a black, sans-serif font, underlined.

Examples – Applications

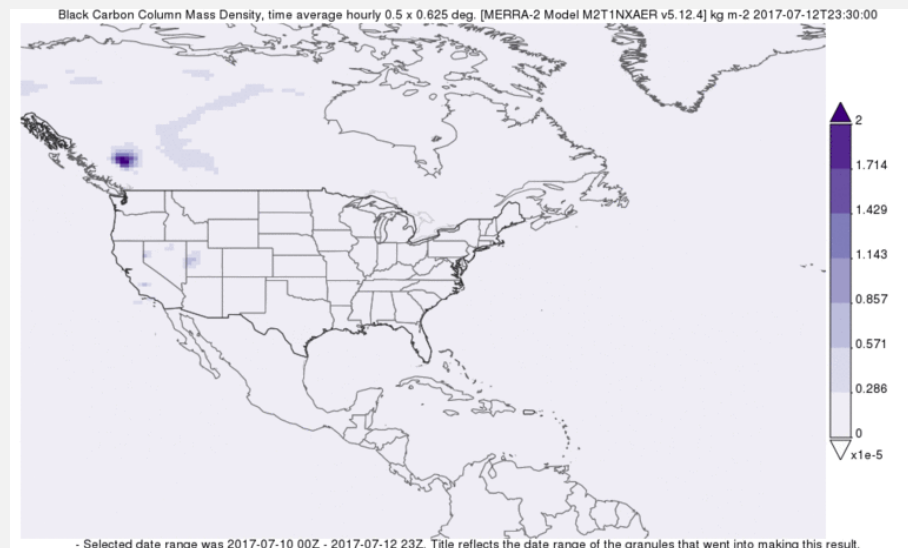
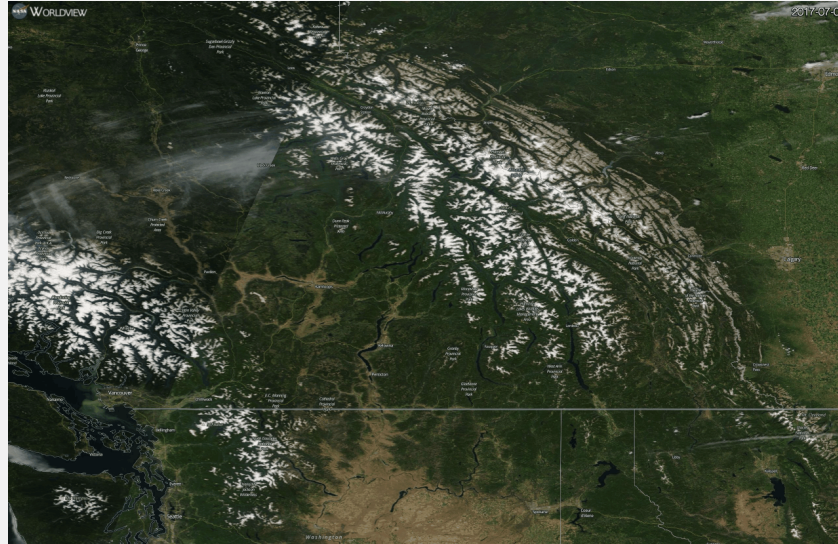
Global Mean AOD Analysis

1980 – Onward

- Unique amongst its peers, the MERRA-2 reanalysis now includes an aerosol reanalysis for the modern satellite era (1980 – onward)
- Aerosols are ***coupled*** to the meteorological reanalysis (both radiatively and through emissions and loss processes)



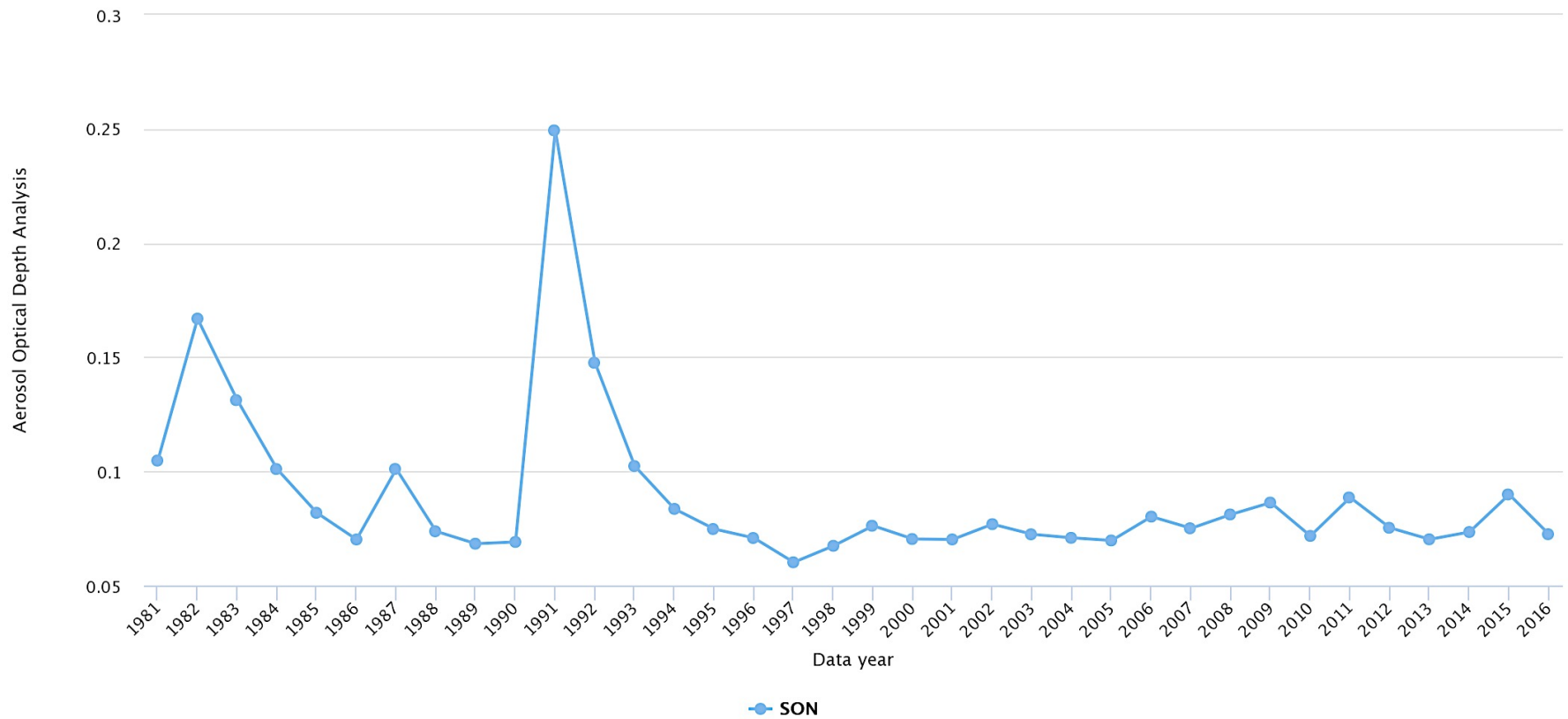
Fires – July 2017



AOD Time Series Over CA

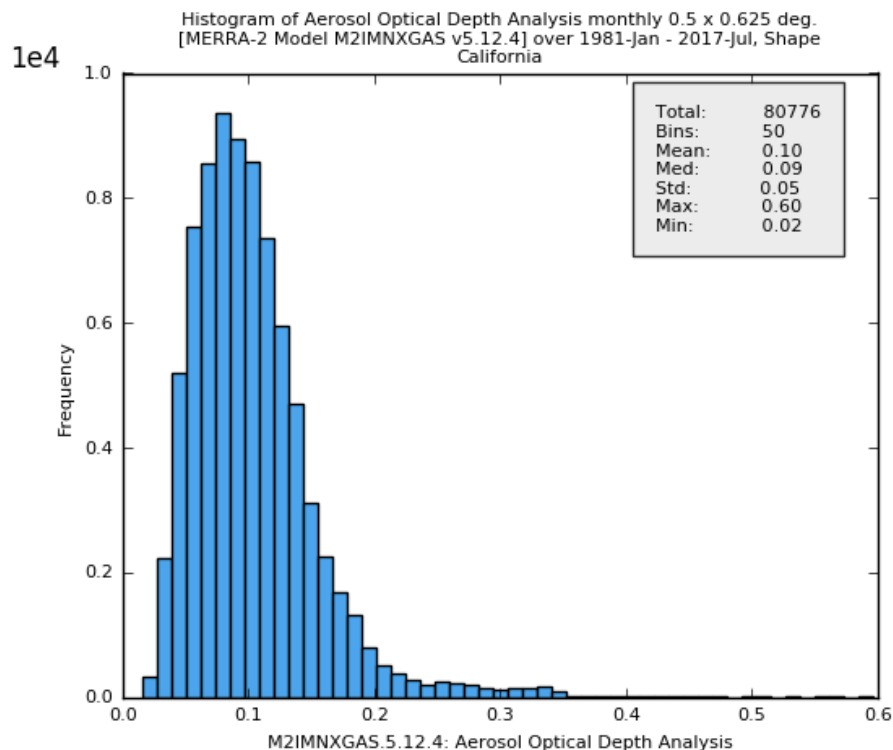
Interannual time series Aerosol Optical Depth Analysis monthly 0.5 x

0.625 deg. [MERRA-2 Model M2IMNXGAS v5.12.4] over 1981-Sep - 2016-Nov, Shape California



Highcharts.com

AOD Distribution Over CA



EARTHDATA
Data Discovery ▾ DAACs ▾ Community ▾ Science Disciplines ▾

GIOVANNI The Bridge Between Data and Science
v 4.23 [Release Notes](#) [Browser Compatibility](#) [Known Issues](#)
MODIS OPeNDAP server continuing problem ... [1 of 2 messages] [Read More](#)

Select Plot
☐ Maps: Select... ▾ ☐ Comparisons: Select... ▾ ☐ Vertical: Select... ▾ ☐ Time Series: Select... ▾
☒ Miscellaneous: Histogram ▾

Select Date Range (UTC)
 YYYY-MM HH:mm
 1981 -01 -01 00 :00 to 2017 -12 -31 23 :59
 Valid Range: 1980-01-01 to 2017-07-31

Select Region (Bounding Box or Shape)
 Format: West, South, East, North
 US States California;

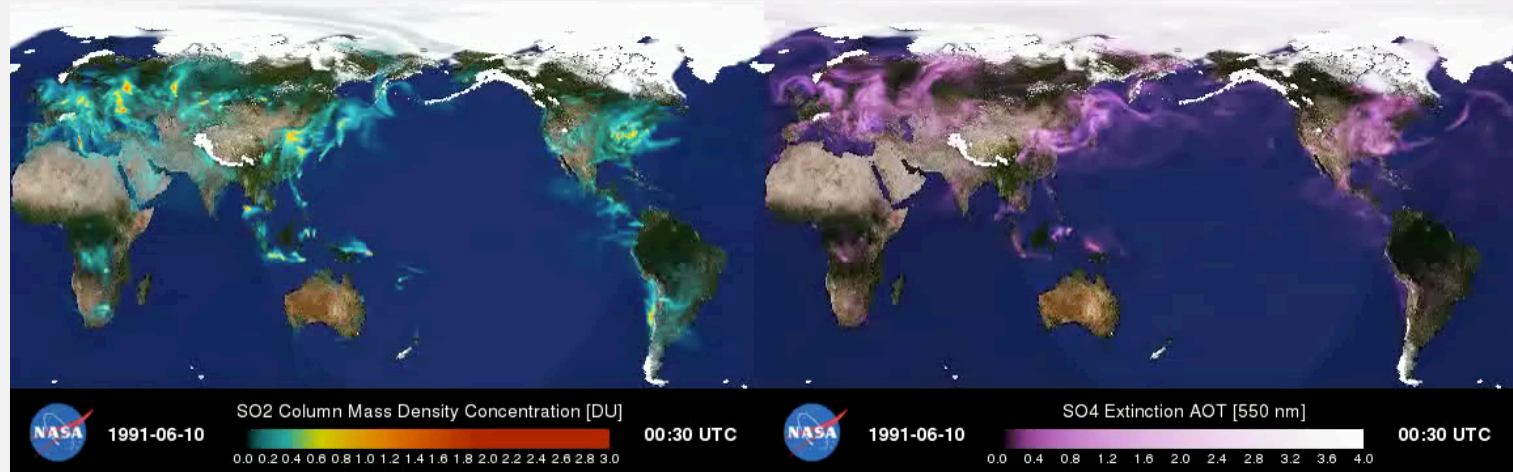
Select Variables
▼ Disciplines
☐ Aerosols (183)
☐ Atmospheric Chemistry (79)
☐ Atmospheric Dynamics (385)
☐ Cryosphere (15)
☐ Hydrology (997)
☐ Ocean Biology (44)
☐ Oceanography (48)
☐ Water and Energy Cycle (1065)
▼ Measurements
☐ Aerosol Index (3)
☐ Aerosol Optical Depth (83)
☐ Air Pressure Anomaly (1)
☐ Air Pressure (51)
☐ Air Temperature (84)
☐ Albedo (21)
☐ Altitude (8)
☐ Angstrom Exponent (17)

Number of matching Variables: 0 of 1735
 Total Variable(s) included in Plot: 1
 Keyword:

Variable	Source	Temp.Res.	Spat.Res.	Beg
<input checked="" type="checkbox"/> Aerosol Optical Depth Analysis (M2IMNXGAS v5.12.4)	MERRA-2 Model	Monthly	0.5 x 0.625 °	198

Help Reset Feedback **Plot Data** Go to Results

Pinatuba Eruption

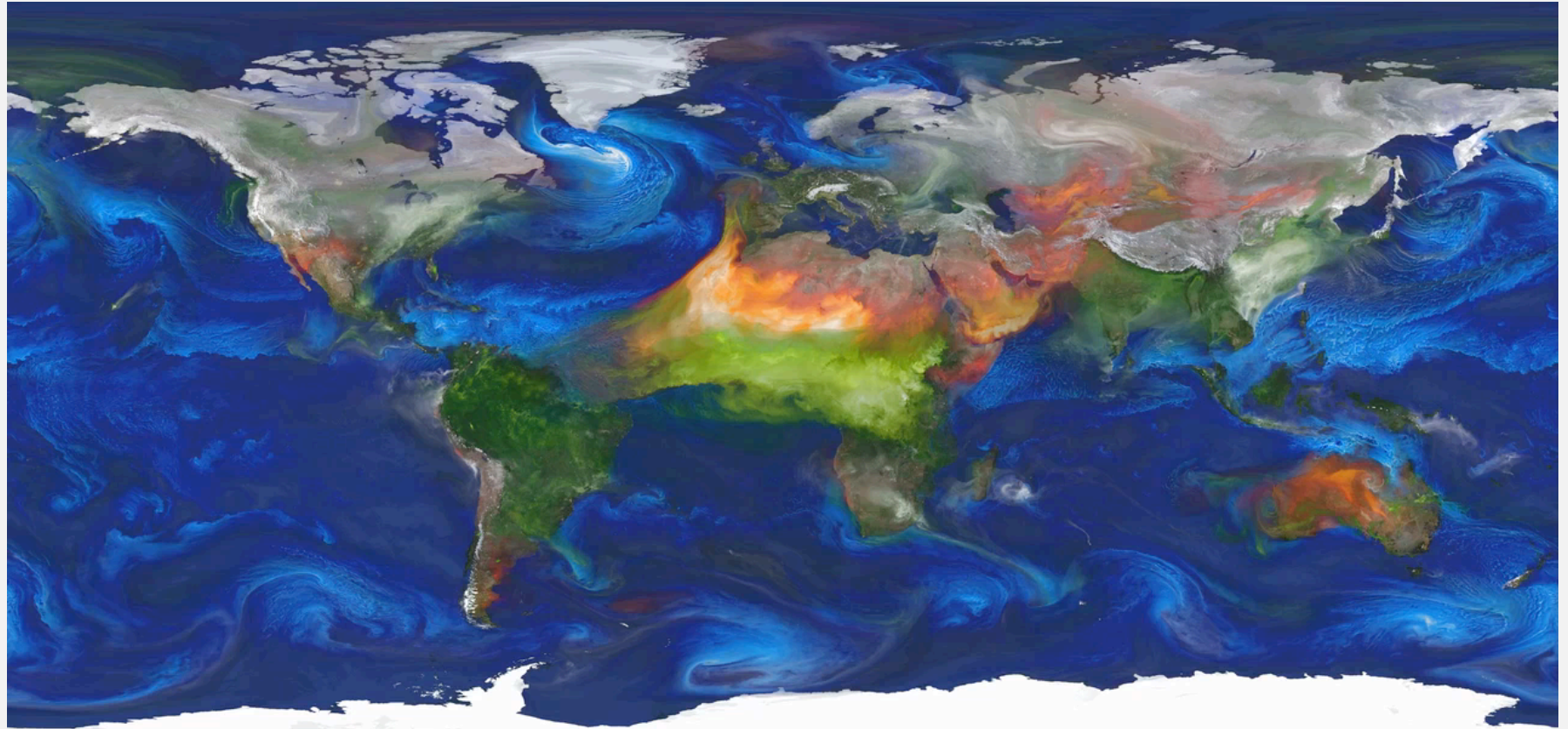


- First aerosol assimilation to include major historic volcano events like El Chichón (1982) and Pinatubo (June 1991)
- Movie shows the co-evolution of gaseous SO₂ emissions from Pinatubo (left) and formation of the sulfate aerosol plume (right) as SO₂ is converted into particles
- SO₂(g) is from emissions inventories and unconstrained by assimilation. Sulfate aerosol AOD (right) is impacted by the assimilation of total aerosol AOD

Summary

- MERRA-2 provides the first integrated aerosol-meteorology reanalysis for the satellite era
 - Aerosols impact the meteorological “first guess”
- Compared to MERRAero, MERRA-2 adds AVHRR, MISR and AERONET data to MODIS
- Caveats:
 - Monthly mean biomass burning emissions inadvertently used during 2000-2010
 - Due to forward processing constraints, MISR/AERONET have been dropped around mid/late 2014.
 - MERRA-2dd: 12.5 km downscaling coming up in 2016

7 km GEOS-5 Nature Run Global Mesoscale Simulation

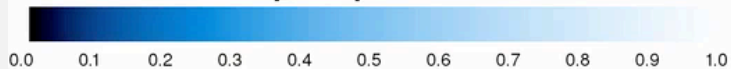


01/01/2006
0000 UTC

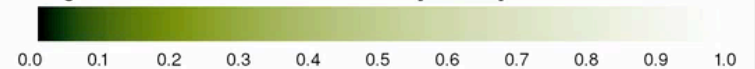
Dust Extinction AOT [550 nm]



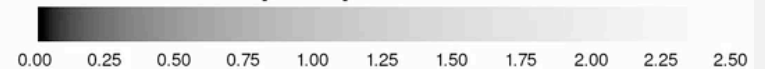
Sea Salt Extinction AOT [550 nm]



Organic/Black Carbon Extinction AOT [550 nm]



Sulfate Extinction AOT [550 nm]



A satellite image of a coastal region, likely the Persian Gulf, showing a semi-transparent rectangular overlay. The overlay contains a lighter, more detailed view of the same area. Red annotations, including circles and lines, are scattered across the overlay, highlighting specific features. The word "Extra" is written in the bottom left of the overlay, with a horizontal line extending to the right.

Extra

GEOS-5

Earth System Model

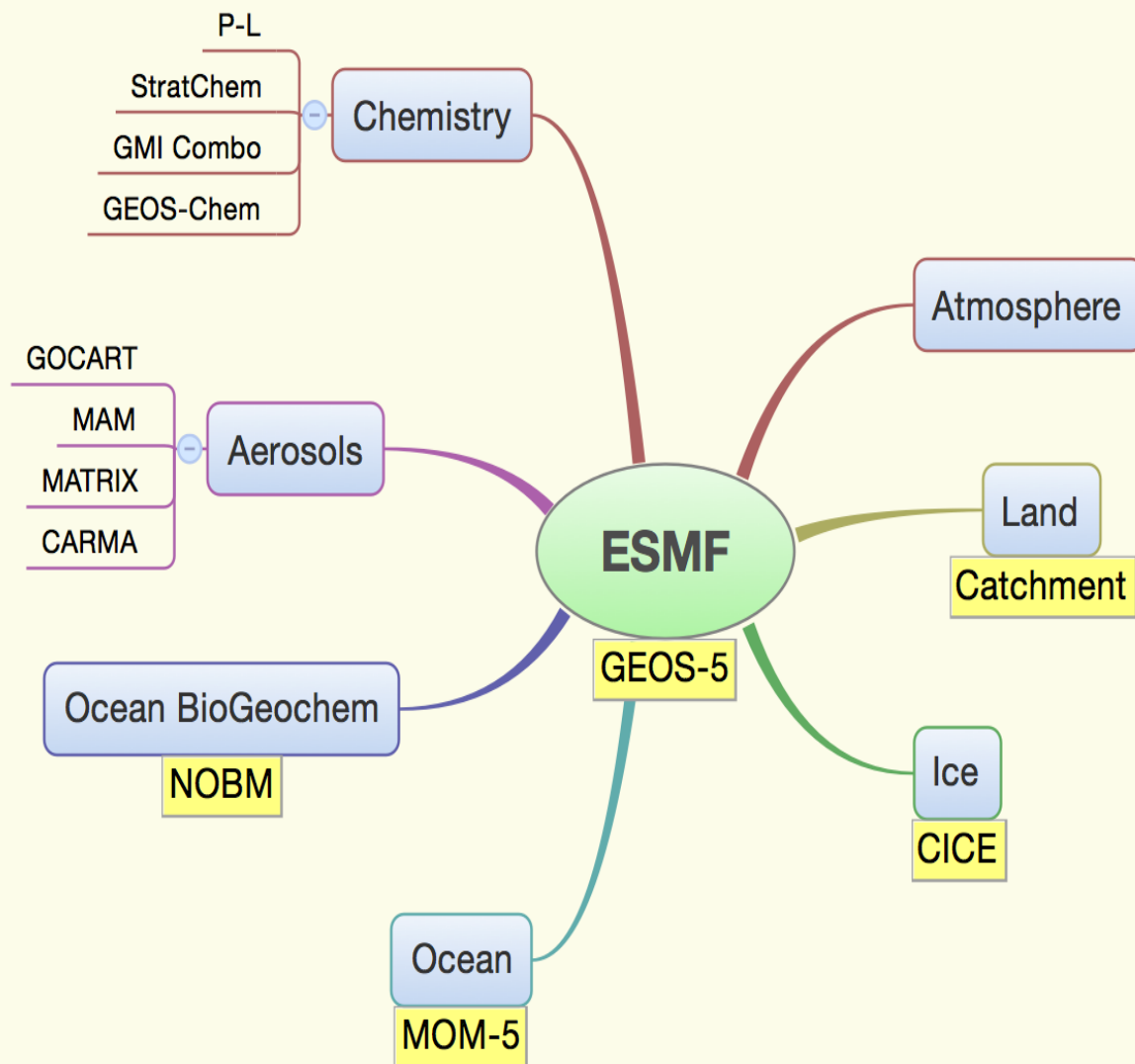


Components coupling via the Earth System Model Framework (ESMF)

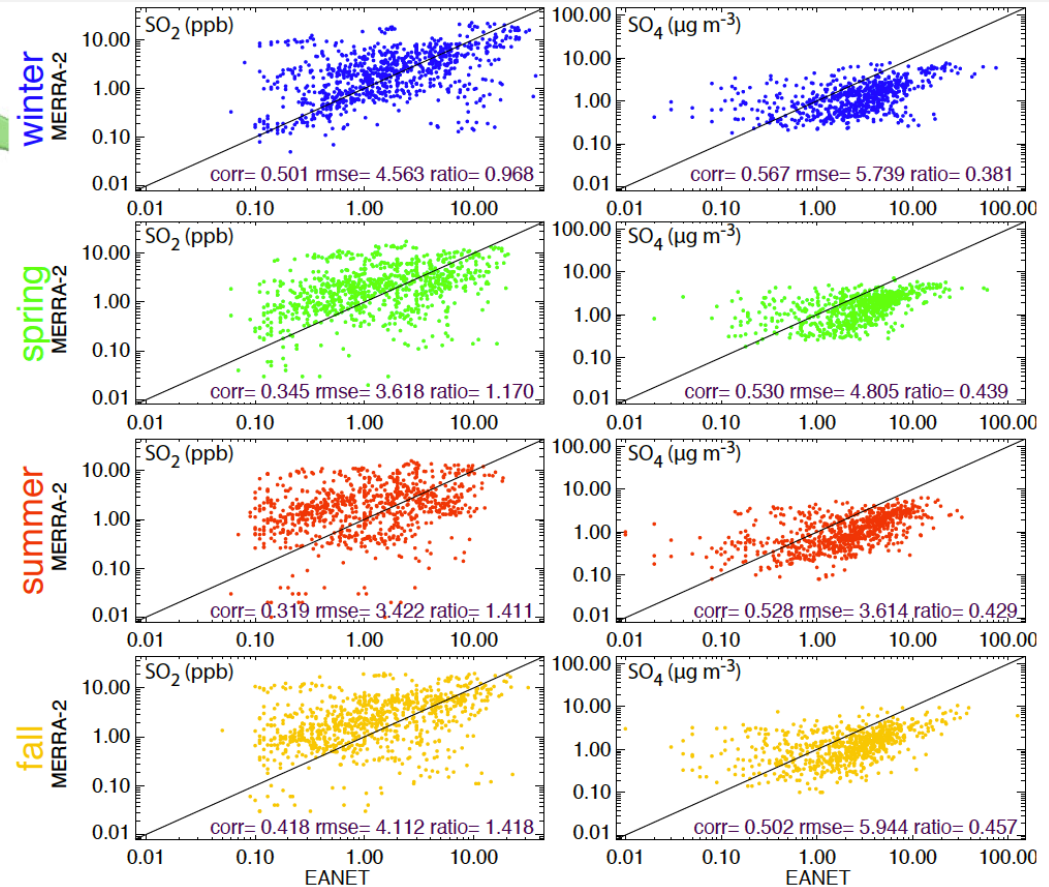
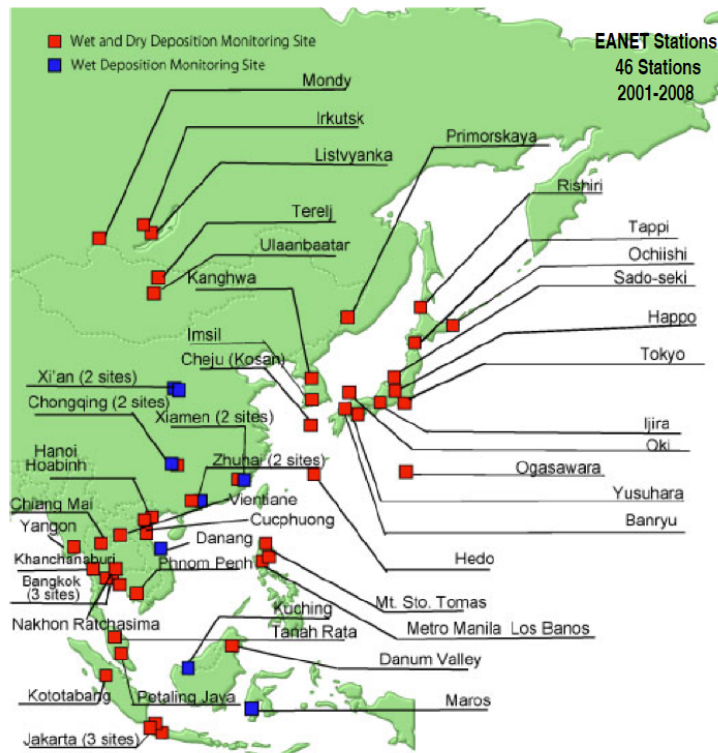
Aerosol and chemistry radiatively coupled to GCM

Applications:

- ☐ Seasonal forecasts
- ☐ Weather and aerosol NRT forecasts
- ☐ Reanalysis
- ☐ Observing System Simulation Experiments (OSSEs)



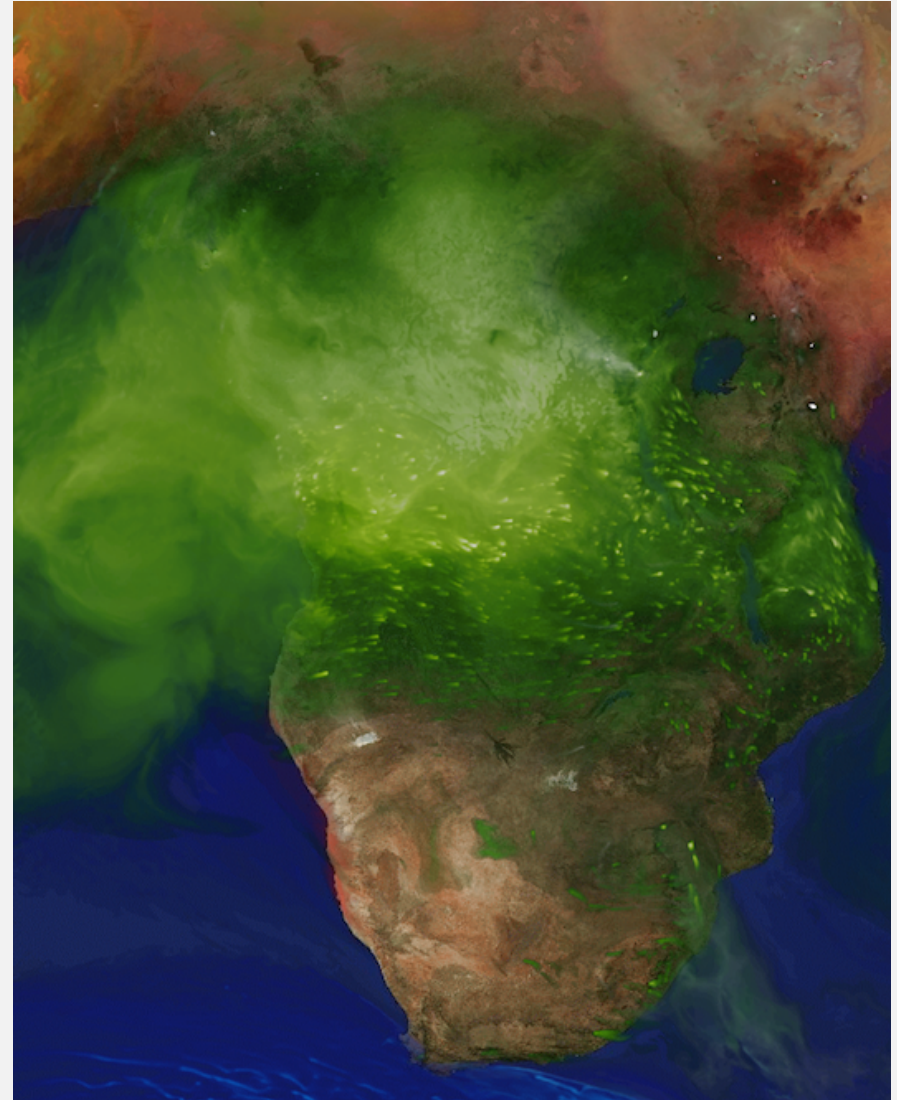
Surface Concentrations: Asia



Surface concentrations from EANET vs. MERRA-2
for 2001 – 2008

QFED: Quick Fire Emission Dataset

- Top-down algorithm based on MODIS Fire Radiative Power (AQUA/TERRA)
- FRP Emission factors tuned by means of inverse calculation based on MODIS AOD data
- Daily mean emissions, NRT
- Prescribed diurnal cycle
- In GEOS-5 BB emissions are deposited in the PBL



GEOS-5 Reanalysis

<http://gmao.gsfc.nasa.gov/reanalysis>

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Reanalysis

Long-term, model-based analyses of multiple datasets using a fixed assimilation system are a major focus in the GMAO. Building on the success of the atmospheric reanalyses conducted with GEOS-5, current research and development activities are directed at producing a major Earth System Reanalysis, including atmosphere, land, ocean, and ice.

MERRA-2

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) provides data beginning in 1980 and runs a few weeks behind real time. Alongside the meteorological data assimilation using a modern satellite database, MERRA-2 includes an interactive analysis of aerosols that feed back into the circulation, uses NASA's observations of stratospheric ozone and temperature (when available), and takes steps towards representing cryogenic processes.

MERRA

The Modern-Era Retrospective analysis for Research and Applications (MERRA) dataset was released in 2009. It is based on a version of the GEOS-5 atmospheric data assimilation system that was frozen in 2008. MERRA data span the period 1980 to the present and are produced on a $0.5^\circ \times 0.66^\circ$ grid with 72 layers. **NOTE: MERRA production will be discontinued at the end of 2015.**

O.S.S.E


Observing **S**ystem **S**imulation **E**xperiment

Model-Based OSSE

- A framework for numerical experimentation in which *observables* are simulated from fields generated by an Earth system model, including a *parameterized* description of the *observational error* characteristics
- Simulations are performed in support of an experimental goal

GEOS-5 Nature Run Data Portal

<http://gmao.gsfc.nasa.gov/projects/G5NR>



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Global Modeling and Assimilation Office

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G5NR Ganymed Release

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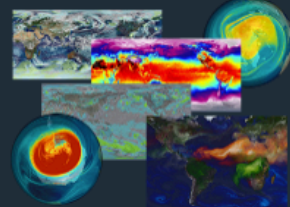
Mailing List


GEOS-5 Nature Run, Ganymed Release

Non-hydrostatic 7 km Global Mesoscale Simulation

The GEOS-5 Nature Run (Ganymed Release) is a 2-year global, non-hydrostatic mesoscale simulation for the period June 2005 through May 2007 with a 7 km horizontal resolution. In addition to standard meteorological parameters (wind, temperature, moisture, surface pressure), this simulation includes 15 aerosol tracers (dust, seasalt, sulfate, black and organic carbon), O₃, CO and CO₂.

This model simulation is driven by prescribed sea-surface temperature and sea-ice, daily volcanic and biomass burning emissions, as well as high-resolution inventories of anthropogenic sources.





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National Aeronautics and Space Administration

Applied Remote Sensing Training Program

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GEOS-5 Forecasts

<http://gmao.gsfc.nasa.gov/forecasts>



National Aeronautics and Space Administration
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GEOS-5 Assimilation

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Experimental Forecasts

Forecast Status Nominal

CHOOSE CATEGORY: ☒ WEATHER ☐ ENVIRONMENTAL ☐ SEASONAL & OCEAN ANALYSES

Weather Analyses and Forecasts

WX MAPS

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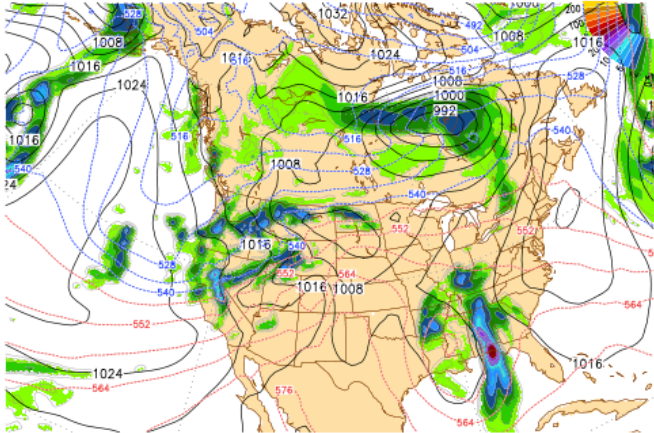
RADIANCES

OBS IMPACT

WMS VIEWER

» INTERACTIVE WEATHER MAPS

NASA/GMAO - GEOS-5 Forecast Initialized Wednesday 22 February 2017 00UTC
3-hr Accum Precip [mm], SLP [mb] and 1000-500mb Thickness [dam]



0-hr Forecast Valid Wednesday 22 February 2017 00UTC

G5NR Data Portal

Documentation

Simulation Images, Animations, and Data

Highlights Images Get Data **Documentation**

DOCUMENTATION

- [File Specification](#). This document has a comprehensive list of datasets available, as well as description of the horizontal and vertical grids.
- [Data Access Guide](#). This wiki page has specific information on the location of our files and instructions on how to access from a variety of applications such as GrADS, Matlab, IDL or even from a C/Fortran program. Sample code is also provided.
- [GEOS-5 Configuration](#). This document documents the particular configuration of the GEOS-5 earth system model used for the G5NR simulation. It includes an overview of the main parameterizations, boundary conditions and emissions files.
- [G5NR Validation](#). This Technical Memorandum documentation on the scientific performance of the G5NR datasets. This is a required reading for understanding the strengths and limitations of the G5NR simulation and its applicability to a given application.